RF Bearing Estimation in Wireless Sensor Networks

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Abstract: *This paper introduces a novel method for bearing estimation based on a rotating antenna generating a Doppler shifted RF signal. The small frequency change can be measured even on low cost resource constrained nodes using a radio interferometric technique introduced previously. Measuring the Doppler shift at two known locations provides a bearing estimate to the rotating node. An alternative approach employing a switched antenna array is proposed that provides improved robustness by avoiding moving parts.*

Keywords: bearing estimation, wireless sensor networks, radio interferometry.

Introduction

While there are many practical localization systems for mobile ad-hoc networks, wireless sensor networks (WSN) and unattended air or ground vehicles, there are still applications with such requirements that none of the existing solutions is satisfactory. GPS, for example, typically does not work indoors and it is also not well suited when low cost and/or very long lifetime are the main design drivers. Techniques based on ultrasonic and infrared signal modalities have short range and require line-of-sight. Clearly, RF-based approaches have many advantages for most applications. A radio is already available on any wireless node, so it comes at no added cost and it is already included in the power budget and RF range is superior to most other signals. Radio signal strength (RSS) based approaches are the most straightforward for estimating distance from an RF signal; however, such methodologies are relatively imprecise due to fading. Ultra Wide Band (UWB) systems are resistant to multipath effects in both communication and ranging. They have accuracy of 1.5m or better. The disadvantage of UWB is that it requires high sampling rates and/or nanosecond-scale time synchronization thus increasing cost. Also, the FCC has limited the maximum power of UWB radio transmissions restricting the maximum range of UWB methods typically to 20m.

Recently, a radio interferometric solution was proposed for the localization and tracking of resource-constrained wireless nodes [1,2]. By measuring the phase difference of a signal generated by two transmitters with close frequencies at two receivers, information on the relative distances of the four nodes involved can be deduced. While both the range and the accuracy of the method proved superior to many other approaches, multipath propagation impacts the accuracy of the method. Also, the ranging needs to be carried out at multiple frequencies which can be time consuming. A variation of the method replaces the phase measurements with that of frequency [3]. The technique assumes a moving transmitter at an unknown location (and with an unknown velocity vector). As such, it generates a Doppler shift. The reference implementation works on Crossbow Mica2 nodes operating at 430MHz. A person walking with the transmitter at 0.3m/s induces a 0.4Hz shift, a 10^9:1 ratio, which is impossible to measure on the CC1000 radio chip or on much more expensive instrumentation either. However, if a second, stationery node transmits a radio signal a few hundred Hz away from the moving node's frequency, the envelop signal (measured as the RSS of the composite signal) has a few hundred Hz frequency. The Doppler shift also appears in this signal and can be measured accurately enough using simple, inexpensive hardware. If this shift is measured at multiple receivers, the location and velocity of the receiver can be accurately estimated [3].

Rotating transmitter

The obvious disadvantage of this method is the requirement for movement, since without that, there would be no Doppler shift. This observation leads us to the idea of rotating the antenna of the transmitter (or even the entire node) at a constant speed and radius. To a stationery observer, the signal will have a continuously changing frequency. Again, radio interferometry is required to be able to measure this accurately. How the frequency changes over time depends on the angular velocity of the transmitter, the radius of the circle, and the distance between the rotating transmitter and the receiver. While it is theoretically possible to compute the distance given the radius and the angular velocity, the result is very sensitive to measurement errors if the distance is large. To tackle this issue, we leverage the fact that the correlation of the observed frequency change across multiple receivers provides valuable information on the location of the nodes involved.

While attractive, this method relies on measuring the Doppler shift at any one receiver accurately. However, in most computers and wireless devices, uncompensated crystal oscillators are used to generate the clock signals. The short-term stability of these oscillators are typically between 10^{-8} and \$$10^{-9}$ for one second. In our case, this corresponds to possibly more than 1Hz error, because we cannot measure the baseline frequency directly (i.e. when the transmitter is stationary). We need to rely on measuring the difference between the maximum and the minimum

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frequencies and take their mean. Since the time between these events may not be much less than one second, short term stability can cause a larger error than the phenomenon we are trying to measure. Notice that the transmit frequency instability has the same effect at two receivers if we compare their measurements at the same time. Hence, if we take the difference of the two measured frequencies, the actual transmit frequency is eliminated. This frequency difference relates to the difference of the observed speeds; however, not having the speed measurements available directly, only their difference, makes solving for the location somewhat more complicated. However, we can obtain the bearing by measuring the power of the difference signal:

$$\alpha = sin^{-1}\left(\frac{\sqrt{2}}{2r\omega}\sqrt{\int_{0}^{\frac{2\pi}{\omega}} \Delta v^2(t)dt}\right)$$

where $\boldsymbol{r}$ is the radius and $\boldsymbol{\omega}$ is the angular velocity of rotation and $\boldsymbol{\Delta v}$ is the measured speed difference.

One might question the practicality of a rotating node. Obviously, in most tracking applications the receivers need to be small and inexpensive, so rotation is not an option. However, in many applications the coverage area is fixed and can be equipped with more expensive, so-called infrastructure nodes. For example, in a mobile application, a few vehicles can have both GPS for tracking their own positions and the rotating nodes for tracking possibly many other low-cost nodes that do not have GPS.

Antenna array

Using a circular antenna array to mimic the rotation of the transmitter, at first, appears to be a straightforward extension of the above approach. At any point in time, only one antenna is transmitting a sinusoid. With uniform periodicity, we turn the antenna off and continue transmitting the same sinusoid via its neighboring one (always in the same direction, e.g. clockwise). If the receiver samples the transmitted signal uniformly such that exactly one sample is taken per transmit antenna, a transmitter array is indistinguishable from a rotating transmitter.

Such a transmitter array can be implemented as follows. The antennas are connected to an antenna multiplexer, which routes the signal to be transmitted from a common signal source to one of the antennas. The antenna to which the signal is routed can be switched programmatically via the antenna multiplexer. The routing of the signal lines assure that the time delay is uniform on all channels of the array, ensuring that whenever a switch from antenna A_i to antenna A_j occurs, the phase of the signal at A_j will be identical to the phase of the signal at A_i.

While using an antenna array instead of a rotating transmitter offers a list of advantages (no moving parts, reduced size, energy efficiency, etc.), it, as is, has limited feasibility. Inactive antennas in the array absorb radio waves radiated by the active antenna and re-radiate them. As a result, at any receiver, the incoming signal will be the sum of the signals from the active and the inactive, parasitic antennas. Assuming that the transmitted signal is a sinusoid, its superposition with the signals from the parasitic antennas causes a phase shift at the receiver. Although there exist approaches to calibrate the antenna array, they typically computationally expensive and need to run periodically, since parasitic antenna effects change with temperature and humidity. Therefore, this approach demands a complex solution which is impractical with simple low-power devices.

Antenna arrangement

To tackle this issue, we propose the following antenna arrangement. Three monopole antennas are arranged such that they are pairwise perpendicular to each other. As a result of this, a transmission on one antenna will never induce a current in any of the other two, eliminating the parasitic antenna effects. The transmit antennas must not be more than half wavelength apart from each other, otherwise the receiver's bearing cannot be unambiguously determined due to spatial aliasing.

Obviously, the antenna of the receiver must be oriented such that it is not perpendicular to any of the transmitter antennas, to allow for receiving the signal from all of them. For the sake of simplicity, we can assume that the tip of the receiver antenna is coplanar with the tips of the transmitter antennas, that is, bearing estimation is done on a 2-dimensional plane.

It is worth noting that it is not possible to arrange more than three antennas in a mutually perpendicular fashion. On the other hand, if an array of only two mutually perpendicular antennas are used (with less than half wavelength antenna separation), the receiver's bearing cannot be unambiguously determined due to symmetry with respect to the plane of the two antennas.

Physical phenomenon

Though it is possible to mimic a rotating transmitter with an antenna array (given a sufficiently large number of antennas in a circular arrangement) and to rely on frequency measurements by the receiver, there is a simpler way to compute the bearing. When the antenna array switches the antenna on which it transmits, an instantaneous phase change can be observed in the incoming signal at the receiver, because location of the signal source is changed (see Fig. 1). The magnitude of the phase change depends on the difference of the distance of the receiver from the two antennas. The bearing of the receiver can be computed from the measured phase changes.

When the transmitter is switching from antenna $\boldsymbol{A_i}$ to antenna $\boldsymbol{A_j}$, the phase change $\boldsymbol{\Delta\varphi_{i,j}}$ observed at receiver $\boldsymbol{R}$ is

dependent on the distance of $\boldsymbol{R}$ from the two antennas and $\boldsymbol{\lambda}$, the wavelength of the transmitted RF signal:

$$\Delta\varphi_{i,j} \frac{\lambda}{2\pi} = d(A_i, R) - d(A_j, R) \quad (1)$$

where $\boldsymbol{d(P_1,P_2)}$ is the Euclidean distance of points $\boldsymbol{P_1}$ and $\boldsymbol{P_2}$, and assuming that

$$|d(A_i, R) - d(A_j, R)| < \lambda.$$

Two such equations, involving different pairs of antennas, are sufficient to solve for R. Hence, *an array of three antennas is sufficient.*

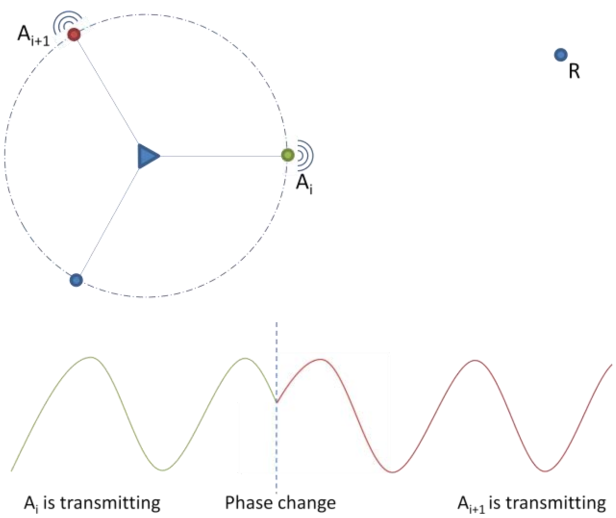

Figure 1. Switching the transmit antenna results in an instantaneous phase change at the receiver

Identifying a switch

The receiver identifies a switch between two antennas of the transmitter array by continuously analyzing the phase of the received radio signal. It stores the value of the phase change as well as the timestamp of the detected occurrence of phase change for further processing.

The measurement of change in phase requires a sampling frequency at least twice the frequency of the sinusoid (Nyquist), which makes this technique very expensive to implement if the transmitted signal has a high frequency. We use radio-interferometry to tackle this issue. An auxiliary antenna is continuously transmitting a sinusoid at a fixed frequency $\boldsymbol{f\text{-}f_i}$, the superposition of which with the sinusoid of frequency $\boldsymbol{f}$ transmitted by the switched antenna, generates an interference field with a beat frequency of $\boldsymbol{f_i}$. If $\boldsymbol{f_i<<f}$, the phase shift of the beat signal envelope approximates very closely the phase shift of the high frequency sinusoid. The frequency shift of the beat signal can be identified and measured event at low sampling rates ($>\boldsymbol{2f_i}$), which drastically reduces the computational requirements of the receiver compared to the non-interferometric solution.

Identifying antennas participating in a switch

In order to compute the bearing, for each switch, the receiver must be able to identify the antennas between which the switch occurs. We encode this information in the time between consecutive switchings as follows. Each antenna switching is assigned a unique integer identifier between $\boldsymbol{1}$ and $\boldsymbol{N}$, where switching $\boldsymbol{i}$ takes place between antennas $\boldsymbol{A_i}$ and $\boldsymbol{A_{i+1}}$. We define an invertible function $\boldsymbol{S}$, called the switch delay function $\boldsymbol{S: i \rightarrow \Delta t}$, which maps the switch identifier $\boldsymbol{i}$ to a time value $\boldsymbol{\Delta t}$. $\boldsymbol{S}$ and its inverse function $\boldsymbol{S_{inv}}$ are known to both the transmitter array and the receiver.

The transmitter array sets the timing of the antenna switches as follows. For a given switch $\boldsymbol{j}$, its time offset from the previous switch is set to be $\boldsymbol{S(i)}$. The receiver, by measuring the time between consecutive switches, decodes the identifier of the most recent switch by applying $\boldsymbol{S_{inv}}$ to the time delay measured between the most recent and the preceding switch. Knowing the switch identifier, the participating antennas, as well as their locations, are established by a table lookup.

It is worth noting that, no time synchronization required between the transmitter array and the receiver. Since the location related information is carried in the phase change that occurs as a result of a switch, and since the phase change does not depend on when the switch occurs, the timing of the switches is irrelevant.

Computing the bearing

We present three alternative methods to compute the bearing of the receiver.

Quasi-doppler method

Let us assume a rotating transmitter with angular velocity ω emitting a sinusoid of frequency $\boldsymbol{f}$, and a receiver in far field, such that the radius of the circle of rotation is negligible with respect to the transmitter-receiver distance. The rotation of the transmitter will induce a time varying fluctuation in the frequency of the received signal at the receiver:

$$f_{received}(t) = f + A\sin(\omega t + B),$$

where amplitude A of the fluctuation depends on the speed of rotation and its phase depends on the bearing.

When a quasi-Doppler antenna array is used in place of a rotating transmitter, the time varying frequency signal (also referred to as the QD signal) cannot be observed directly. Instead, the receiver measures instantaneous phase changes

when an antenna switch occurs. The phase change measured between time ***t*** and ***t+Δt*** can be expressed as:

$$\Delta\varphi(t, t+\Delta t) = \frac{\int_t^{t+\Delta t} f_{received}\ (t)dt}{\Delta t}$$

It can be shown that, for a fixed ***Δt***, this is a sinusoid with frequency identical to that of the rotating antenna. Hence, as long as the Nyquist limit is observed, the fluctuating frequency signal can be reconstructed from phase change measurements.

The fundamental frequency of the observed QD signal is determined by how fast the antennas are switched. But it is irrelevant, the only important thing is that we have ***n*** samples of this signal per period, where ***n*** is the number of antennas, regardless of how fast they are being switched. If the receiver is far from the transmitter relative to the radius of the antenna array, then this signal is close to a pure sinusoid. The phase of this signal can then be estimated in a number of different ways. For example, the phase change data can be gathered for multiple rotations, and then an FFT with high enough resolution can be performed. The phase of the peak at the fundamental frequency gives the bearing. Note that the fundamental frequency is very precisely known: it is exactly one $\boldsymbol{n^{th}}$ of the sampling rate.

Intersection of hyperbolas

We notice that equation (1) constrains the location of the receiver ***R*** on a hyperbola with foci ***A*** and $\boldsymbol{A_j}$. In the general case, two phase change measurements using with different antenna pairs yield two hyperbolas, the intersection of which yields the location of ***R***.

Intersection of two hyperbolas can be computed analytically when the two hyperbolas share a common focus (see [4] for more details). This is exactly the case with the switched antenna array: two consecutive antenna switchings yield two hyperbolas that share a common focus. A switch from antenna $\boldsymbol{A_i}$ to antenna $\boldsymbol{A_j}$ constrains the location of receiver ***R*** to a hyperbola with foci $\boldsymbol{A_i}$ and $\boldsymbol{A_j}$, while a consecutive switching from $\boldsymbol{A_j}$ to $\boldsymbol{A_k}$ constrains ***R*** to a hyperbola with foci $\boldsymbol{A_j}$ and $\boldsymbol{A_k}$, $\boldsymbol{A_k}$ being the common focus.

This implies that an array of three antennas is sufficient to measure the location of the receiver. The locations of the antennas within the array, as well as the order of antenna switchings, can be arbitrary.

In practice, the computed location is very sensitive to errors in the phase change measurement when the receiver is far from the antenna array. Interestingly, the error of the bearing of the location remains relatively small. The intersecting hyperbolas are very close to their asymptotes around the point of intersection. The tangents of both intersecting asymptotes are close to the tangent of the line going through the origin to ***R***, therefore the asymptotes intersect at a small angle. When the computed position of the receiver is expressed in polar coordinates, the error will mostly manifest itself in the radial component.

An estimate of the bearing of ***R*** is computed for every three consecutive phase change measurement.

Far field assumption

Since in a practical application, the distance between the antenna array and the receiver is large compared to the antenna distances within the array, bearing estimation can be simplified using the far field assumption.

Instead of computing the intersection of hyperbolas, we can simplify the solver to compute the intersection of the hyperbolas' asymptotes. We found that if the receiver is more than 3 wavelengths away from the array, the bearing error resulting from the far field assumption is less than the bearing error stemming from the measurement noise.

Conclusion

In this paper, we described an RF bearing estimation technique which can be implemented using very simplistic hardware. We proposed an RF Doppler based as well as a quasi-Doppler solution, along with three alternative ways to compute the bearing of low-power RF receivers.

In the future, we plan to experimentally verify the performance of these approaches and to investigate the feasibility of a low-power hardware implementation.

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